Telecommunications IT and Navigation for Future Mars Exploration Missions
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Abstract- There are three primary drivers behind current investments in telecommunications information technology and navigation. One is finding ways to maximize the volume of science data returned from missions since instrument data generation often exceeds communication bandwidth. Another is to provide the necessary technology to enable networked spacecraft around Mars. The third driver is to enable more precise landing so in-situ vehicles can be placed in the more scientifically interesting regions. This paper describes current NASA investments in these areas funded through the NASA Mars Technology Base Program NRA. The research described in this paper is for stereo image compression, next generation Mars relay protocols, and a capability for autonomous approach navigation using in-situ Mars orbiter assets.

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INTRODUCTION

Current experience has shown that stereo images make up a large proportion of the data return from Mars rovers. The current state-of-the-practice is that stereo image pairs are compressed as independent images, i.e., the correlation between such the pairs is not exploited. One technology development effort is developing compression techniques that leverage these correlations to achieve up to 25% more effective compression. A flight-ready software module is being produced and will be made available to the Mars Science Laboratory (MSL) and other missions. In addition, the effects of this lossy compression technique on scientific value and navigation performance will be evaluated. Improved data compression translates to increased data return and/or lower power transmitters and/or higher quality images. Compared to other link technologies, the return on investment is expected to be high.

The Mars approach navigation technology development effort is producing a prototype capability for autonomous final approach navigation that can be enabling for pinpoint landing and can increase aerocapture reliability. The Mars Network, using the Electra transceiver, will provide a viable and available resource to accomplish autonomous approach navigation. An approach vehicle carrying Electra with a link to a Mars Network orbiter would be able to collect radiometric tracking data, and, with Electra's processing capability, would then process this data to produce extremely accurate realtime trajectory solutions. Simulations have shown that this data can yield sub-300m accurate solutions at atmospheric entry, a critical factor for enabling sub-1km accurate pinpoint landing. This process also needs to be autonomous because there is insufficient time for an Earth-based ground team to provide navigation updates to a Mars approach vehicle in its terminal mission phase.

The complexity and scope of Mars exploration in the next decade promises to provide new challenges to end-to-end telecommunications operations that will require a carefully designed, tested, and optimized stet of communications protocols. Towards that end, a candidate suite of protocols for use in Mars missions is being developed and tested in a realistic real-time simulation that also includes flight hardware implementations. The candidate protocol suite consists of a combination of current communication protocol standards plus Delay-Tolerant Networking (DTN) protocols. These are being refined using high fidelity end-to-end communications system modeling and actual testing of the suite in a flight-like computing environment. DTN will enable current labor-intensive manual link scheduling to be replaced with automated communications protocols. This will provide Mars missions with the ability to communicate from scientists to instruments without having to worry about whether or not an end-to-end path *currently* exists. This will free scientists and mission operations personnel from having to track the details of the communications schedule. The technology will also increase data return and reduce operations costs by automating routing and data reliability processes.

NEXT GENERATION MARS PROTOCOL SUITE

Introduction

In 2004, NASA landed two spacecraft, the Mars Exploration Rovers Spirit and Opportunity, on the surface of Mars. The rovers have returned an extensive amount of data in a mission that has far exceeded the pre-launch life expectancy of the twin spacecraft. Over 95% of the science product returned from these explorers has been telemetered by relaying the data through spacecraft orbiting the planet, primarily Mars Odyssey but also, in some instances, Mars Global Surveyor and Mars Express. As additional spacecraft arrive at Mars, they will either become part of the relaying infrastructure, such as the Mars Reconnaissance Orbiter, or will make use of the infrastructure, as will the Mars Phoenix lander scheduled to be launched in 2007.

Currently, the typical architecture onboard the orbiters for performing relays is to have a circular buffer in which data packets from the surface assets are stored on the same Solid State Recorder as the science data for the orbiter. The data is then downloaded when bandwidth is available on the Deep Space Network. Mission operations personnel coordinate the transmission of this data through a two phased approach of monthly and weekly planning meetings. [1]

While the extensive amount of data returned from the rovers has demonstrated this architecture to be functional and successful, as the number of assets both on Mars and in orbit increases, the complexity of preplanning all the communication paths of these missions has the potential to be overwhelming. Also, as organizations outside of the JPL team operate spacecraft at Mars it will become problematic to plan across disparate organizations. From a system perspective, this architecture precludes the ability of the landers to delete data until it is confirmed on the ground (which can take many minutes or hours due to round trip light time (RTLT), line of sight, or operational delays), does not allow for prioritizing of data across missions and instruments, and does not provide a well-documented standard by which future missions can "plug-and-play" into the Mars network infrastructure.

In 2004, NASA awarded a contract to The Johns Hopkins University Applied Physics Laboratory (JHU/APL) and NASA/JPL to develop a suite of "next generation" protocols for future Mars missions in response to a NASA Research Announcement. The goal of this project is two-fold: 1) to model and simulate future Mars networks and 2) to develop flight software implementations of selected protocols. The two key elements of selected protocols are the Licklider Transmission Protocol (LTP) and the Bundle Protocol (BP) and the target is to have these at Technology Readiness Level Six by the end of fiscal year 2006. The responsibilities on this project are divided between NASA/JPL performing the simulations with input from JHU/APL and JHU/APL engineers developing the flight software.

Licklider Transmission Protocol and the Bundle Protocol

LTP is long haul protocol which provides a reliable service across a deep space link. Evolved from the retransmission procedures of the CCSDS File Delivery Protocol (CFDP), LTP ensures that data sent from a spacecraft to the ground or vice versa are received correctly without the additional overhead of manual verification of the data. BP is a standard method for performing store-and-forward. This is essential for a Mars network as typically data from a rover or lander is not sent through a real-time relay link. Instead data must be stored on the orbiter to await transmission. In a Mars relay environment, BP and LTP would be used in conjunction with another. The flight software would create a bundle of data as received from a landed asset, store it for later transmission, and then use LTP to ensure its delivery to Earth. [2] [3]

Figure ## shows where LTP and BP fit into a typical protocol stack for Mars communication. This diagram depicts how an application would use both BP and LTP for transmission of data from Mars to Earth. The application onboard the spacecraft, either at the instrument level or within the Command and Data Handling (C&DH) software, would package the data into one or more bundles. These bundles provide a consistent unit of operation across the heterogeneous networks in use in deep space communication. Once the bundle is defined, it is transmitted via the reliable Proximity-1 protocol to the orbiting spacecraft. The bundles that constitute the original data can be sent through multiple orbiters and reassembled at the destination location.

Upon receipt at the orbiter, the bundles are stored until an available transmission period is available to the Earth. At that point, the spacecraft and the ground use the reliable LTP protocol to transmit the data to the ground. The BP router at the ground station can determine where this particular data bundle is destined, such as a Principal Investigator facility, and send it to that location. Once all the bundles for a given data set are received, the BP software at the final destination reassembles the data and provides it to the application software for processing.

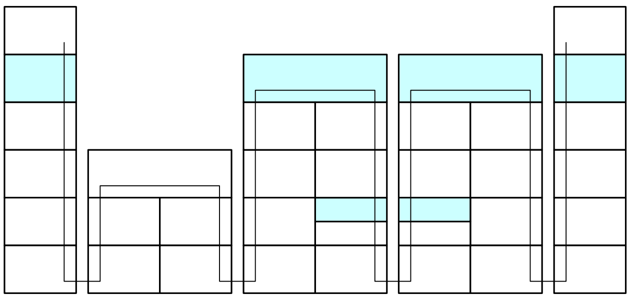


Figure 1 – LTP/BP Protocol Stack

Advantages of LTP/BP

The use of LTP and BP provide the following advantages:

(1) LTP/BP provides a standardized method of store-and-forward communication which is essential for cross organizational relay operations.

(2) LTP/BP allows for data to be deleted from a landed asset upon confirmation that the data has been received by the orbiter. This in contrast to current operations that require manual deletion of data from the ground.

(3) BP enables varying levels of prioritization of data traffic through a Mars Network. Currently, no method of prioritization is used for MER relays.

(4) BP is delay tolerant. Bundles can be produced without concern for when they will be transmitted during a subsequent DSN link opportunity.

(5) A mechanism of retransmission is provided similar to the currently flying CFDP, but without the need to use files.

(6) LTP/BP provides a method to "close the loop" at the ground station instead of at the mission control center. For Mars relay data, this would be useful in that the relay data could be resent or routed when it initially reaches Earth instead of having to be transmitted to a JHU/APL MOC/SOC and then routed a NASA/JPL or another organization's MOC/SOC.

(7) Ground stations, the MOC, mission operators' workstations, and even scientists' workstations can all be peers on the same DTN overlay network. LTP/BP can streamline operations by removing staging and copying of data, by turning the store-and-forward gateway functions over to the DTN nodes.

(8) Allows CFDP to operate in a simplified, unacknowledged mode of LTP/BP.

(9) Unlike CFDP, BP does not require files to be used and also provides the ability to perform parallel transmission of portions of a data set across multiple relay orbiters.

First Year Accomplishments

A set of current and future Mars scenarios have been developed to examine the use of LTP/BP in deep space. These architectures will be run through models developed to the current LTP and BP specifications which have been included in MACHETE, JPL's space network modeling suite. A flight implementation of LTP is being tested and an initial version of BP is available for further tuning for a spacecraft environment. The flight software implementations will be placed in JPL's Protocol Test Lab (PTL) for high fidelity simulations of a typical Mars relay architecture.

STEREO IMAGE DATA COMPRESSION

Introduction

Mars rovers make extensive use of stereo imagery. In spite of this, stereo image pairs from Mars rovers are presently compressed as two independent images, without taking advantage of the large inter-image correlation. We are developing practical data compression techniques for joint compression of stereo image pairs that avoid introducing new compression artifacts. These techniques take advantage of inter-image correlation, and we project they will achieve up to 25% more effective compression, relative to the "ICER" compressor used by the Mars Exploration Rovers. This work will culminate in the development of a flight-ready software module that will be made available to the Mars Science Laboratory (MSL) and other missions.

Significance and Technical Description

The predominant strategy of previous stereo image compression work, including that of [4-8,10-16], has been to compress the left image with conventional methods, produce an approximate right image from the left image and correlation information, and compress the residual image formed by subtracting the approximate right image from the actual right image. This residual right image can be compressed more easily than the original right image. The correlation information generally consists of disparity vectors that indicate offsets between similar regions of the left and right images. The disparity vectors are also encoded in the compressed bitstream. In terms of image quality metrics such as mean-squared-error (MSE) or peak signal-to-noise ratio (PSNR), these methods achieve a significant improvement over compressing the images individually; this improvement can be about 0.25 bits/pixel compared to individual compression to 1.0 bits/pixel. Unfortunately, these methods inherently produce asymmetrical distortion between the reconstructed images: the left image will have artifacts typical of the underlying compression method, while the right image will have these artifacts plus distortion features that are inversely correlated with the goodness-of-match between the images (although the right image may have the same MSE). This effect would reduce the value of the resulting images. Note that although lossy image compression in general is extensively used and well-accepted by Mars missions, this is largely because great efforts have been made to limit objectionable compression artifacts.

Our approach is to implement a wavelet-based stereo image compressor that exploits the correlations between the images in a fundamentally different way than in the general strategy mentioned above. To better describe our approach, we first give some background on modern wavelet-based techniques for compression of single images.

A wavelet transform is a linear (or nearly linear) transform designed to decorrelate images by local separation of spatial frequencies. In wavelet-based image compression, a wavelet decomposition is applied to the image, producing several subbands, each a smaller version of the image, but filtered to contain a limited range of spatial frequencies. The subbands are quantized, either directly or implicitly; this quantization is the irreversible or lossy step in the compression process. The quantized subband data is losslessly encoded.

During encoding, correlation remaining in the quantized subband data is exploited in two ways. First, the value of a sample is predicted from previously encoded samples so that only the difference between the sample and its predicted value needs to be encoded. This is a form of predictive compression. Second, each sample is classified into one of several contexts based on previously encoded samples. A model is maintained of the statistics of samples within each context, allowing the samples to be compressed more effectively. This process is known as context modeling. Finally, the samples are losslessly encoded, with the help of their estimated values and context statistics, in the entropy coding stage.

Our stereo pair image compressor transforms and quantizes both the left and right images in (essentially) the same manner as when the images are compressed individually. As in other approaches to stereo compression, we produce an approximate right image from the left image and correlation information. However, instead of forming a residual image, we exploit the similarity between the approximate right image (which will be available to the decoder) and the actual right image in the context modeling and predictions stage. The standard two-dimensional context modeling and prediction stage is modified to include in context definitions the value of samples at a corresponding location in the approximate right image. Probability estimates, and thus compression effectiveness, are improved in regions where a good match exists between features in the stereo pairs.

The ICER image compressor [9] served as the starting point for our stereo compressor, which we refer to as stereo ICER. ICER, developed at JPL, is a wavelet-based single-image compressor that uses bit-plane encoding of subbands to achieve progressive compression. The Mars Exploration Rover (MER) mission relies on ICER for all lossy image compression.

Unlike approaches that encode one image of a stereo pair followed by a residual image, our stereo compression approach avoids distortion asymmetry between the two reconstructed images. In fact, we are able to produce compression in which the reconstructed images are the same as those produced by ICER, but with lower compressed data volume.

Graphically, independent compression of the two images with ICER proceeds approximately as shown in Figure 2. Figure 3 gives an analogous representation for our stereo compressor, with an example of projected bit rates.

As part of our research, we are conducting an investigation to characterize and quantify the effects of lossy image compression on the accuracy of stereo ranging algorithms. This investigation will be applicable for our stereo compressor as well as conventional (non-stereo) compression techniques. The results of this portion of the investigation will be reported at a later date.

First Year Accomplishments

We have completed prototype/testbed stereo compression software (stereo ICER) that makes use of inter-image correlation in the context modeling/prediction stage of compression, thereby successfully performing lossy compression without introducing new compression artifacts. Currently, the gains achieved from exploiting the inter-image correlation are modest, but we expect them to increase significantly as our methods become more sophisticated. We note that this is the first known implementation of lossy compression of stereo image pairs in which stereo correlation is successfully exploited without introducing new compression artifacts.

Figure 2: Independent compression of the left and right images.

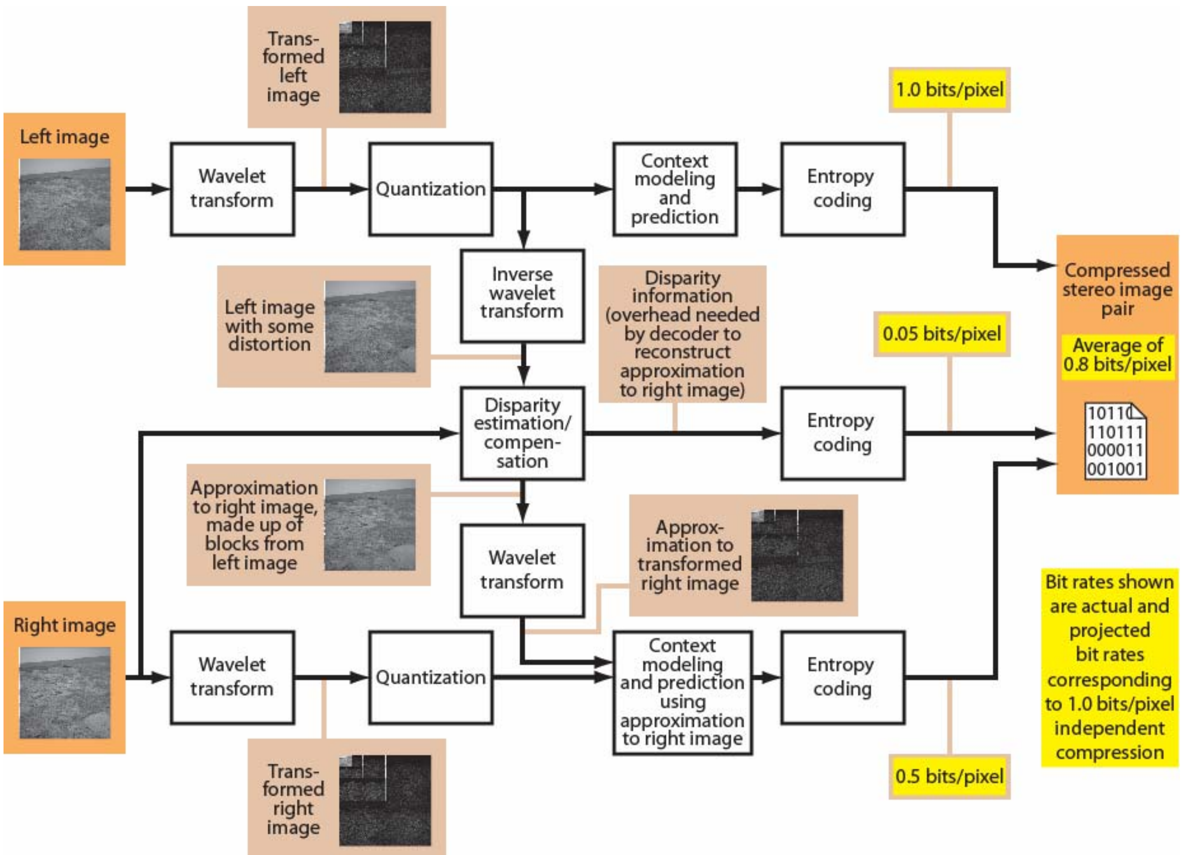
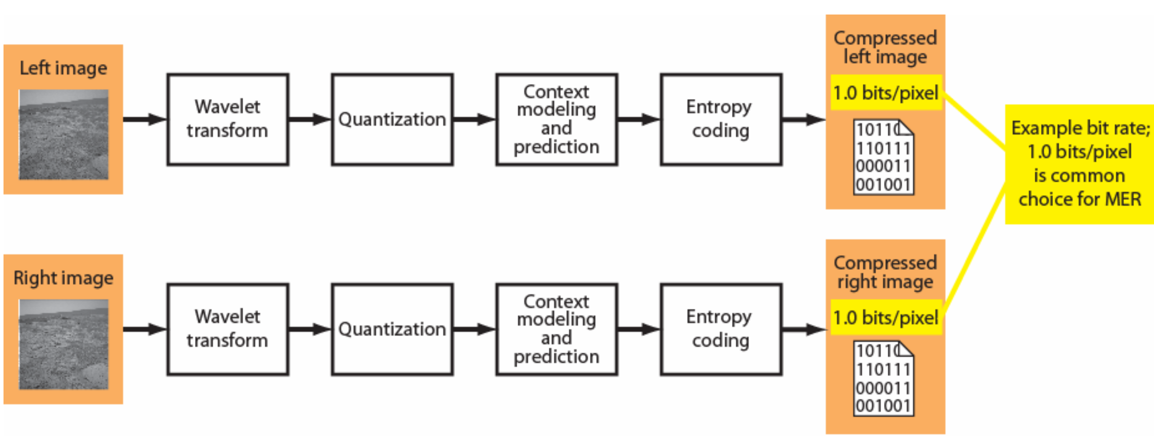


Figure 3: Joint compression of the left and right images. This approach results in the same reconstructed images as with independent compression, but with fewer bits



As an example of our current results, we have applied our compression to the stereo pair shown in Figure 4, and compared the bit rate achieved to that of independent compression with ICER. For these results the left image was compressed losslessly, and the compression of the right image was lossy. By design, both ICER and stereo ICER compress the left image in the same way, achieving 8.51 bits/pixel. For the right image, the quality level achieved with ICER using 0.94 bits/pixel was achieved with stereo ICER using 0.83 bits/pixel, including the overhead needed to generate the approximate right image from the left image. The improvement for the right image is thus approximately 12%. Because the left image was compressed losslessly (due to limitations in our software at the time of this test), the overall percentage improvement for the pair is very small. We have reason to believe, however, that similar results for the right image will hold when the same degree of lossy compression is used for both the left and right images. If one accepts this premise, then we can achieve an overall gain of about 6% compared to independent compression of both images to about 1.0 bits/pixel. This is still far from our projected goal of 25%, but our reasoning that suggested we could achieve 25% improvement still appears to be valid and achievable with further work. We reiterate that the reconstructed images for this comparison will be exactly the same in stereo ICER as in ICER, but the compressed file sizes will be smaller with stereo ICER.

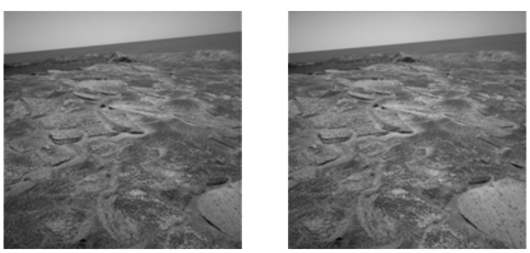


Figure 4: Original stereo image pair.

MARS APPROACH NAV USING IN-SITU ORBITERS

Overview

Achieving key scientific goals of the Mars Exploration Program, including the search for water and life, will require placing landers at locations of the greatest scientific interest. [17] The capability to land within 1 km of a pre-determined site will enable landing and roving to this site while avoiding potential hazards that might lie near its vicinity.

It stands to reason that in order for a guidance system to succeed with a pinpoint landing that precise trajectory knowledge will be required. In particular, this is true during the mission's final phases when the vehicle is actively guiding itself – which include the final approach phase, entry/descent/landing (EDL) phase. For the purposes of this technology effort, *final approach* is defined to be the period from ½ day out to just before entry at the top of the atmosphere. An illustration showing these mission phases is exhibited in Figure 5. Also shown is the initial approach phase – here accurate trajectory knowledge is useful for minimizing Mars targeting errors, but is mostly an Earth ground based activity because there is sufficient time to relay telemetry and uplink commands. It is the final, and most critical, mission phases that precise trajectory information provided to an on-board guidance system can be most useful for enabling pinpoint landing.

These final mission phases are also characterized as brief, and, because of light time delays, proceeding without ground-based Earth support. The implication is that an approach vehicle's trajectory knowledge needs to be obtained *in-situ* and processed *on-board*. The shows the performance of several navigation and guidance strategies for Mars landing, including the current baseline tracking strategy that uses only Earth based radiometric data (Row 1), and an approach using Mars Network (MN) based spacecraft-to-spacecraft radiometric data (Rows 2 & 3). First, a few notes about the columns:

The state of the art landing system is the Mars Exploration Rover (MER) (shown in the table as the three boxes outlined with the wavy border), which yields final delivery errors to the top of the Mars atmosphere of 9 km. Since MER's entry is ballistic these errors grow to 80 km by the time it reaches the surface. Consider that even with active guidance during entry (as with the Mars Science Laboratory), the surface delivery errors (~ 10 km) do not decrease to less than the entry errors without further tracking data. Indeed, it is an accurate statement to say, that in order to even consider pinpoint landing accuracies of less than 1 km requires that an approaching/entering vehicle's guidance system have real time trajectory knowledge updates at this same level of accuracy during final approach. Pinpoint landing that is aided with Mars Network navigation during both final approach and EDL and integrated with active guidance is represented in the table as the last row (#3). This case illustrates that final approach navigation is enabling for pinpoint landing, without it the best that a lander could hope to achieve is the MSL baseline result of a 10 km surface delivery error.

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Figure 7: Illustration of a Mars lander during initial approach, final approach (the subject of this task), and entry, descent, and landing (EDL)

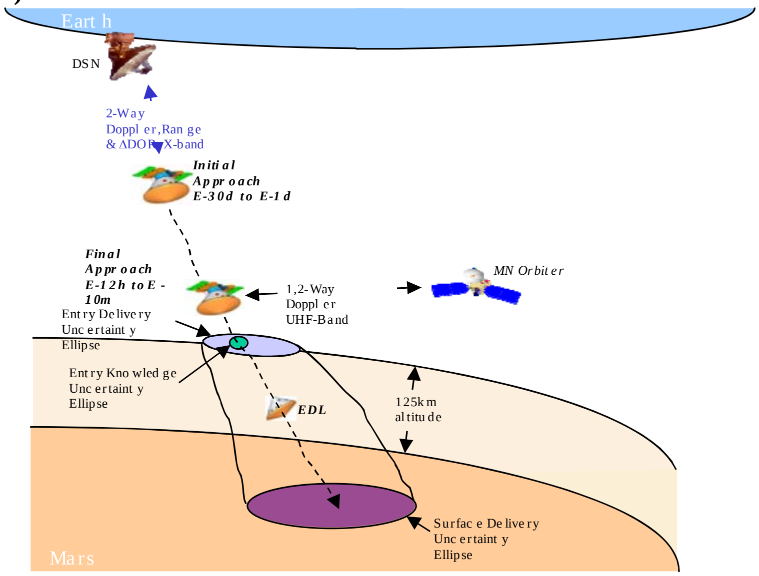

Table 1: Atmosphere entry and surface delivery errors of a lander using DSN only or DSN + Mars Network radiometric tracking for various guidance strategies. Wavy line = state of the art, Gray box = this task

Radio Navigation Capability	3σ Entry Uncertainty (km)		3σ Surface Delivery Uncertainty (km)			Comments
	Knowledge	Delivery	Ballistic (MER)	Hypersonic Guided Entry (MSL)	Hypersonic + Chute Guided Entry	
1) Ground Based X-Band DSN Radio Nav. (Doppler, Range, ΔDOR), E-18 hr data cutoff, E-6 hr maneuver, trajectory update at E-4 hrs	1.5 x 1.5	9 x 1.5	80 x 12	10 x 5	10 x 5	Baseline tracking for MER and MSL. Chute guidance of no value without additional tracking
2) 1 + S/C to S/C UHF-Band Doppler using the MN, autonomous processing begins at E-10 hrs, maneuver at E -1 hr	0.3 x 0.3	0.3 x 0.3	38 x 5	3 x 3	3 x 3	Improved entry knowledge improves MER and MSL case.
3) 2 + additional UHF data through EDL	0.3 x 0.3	0.3 x 0.3	38 x 5	3 x 3	0.5 x 0.5	Improved entry knowledge with EDL beacon nav enabling for pinpoint landing.

1. *Entry knowledge uncertainty represents the trajectory uncertainty at the top of the atmosphere given the proposed tracking strategy in stated each row.*
2. *Entry delivery uncertainty represents the trajectory uncertainty at the top of the atmosphere when the knowledge (up to a certain data cutoff time) is used with guidance.*
3. *Ballistic surface delivery represents an unguided entry, descent, landing (such as with MER)*
4. *Hypersonic guidance represents guidance in the upper atmosphere.*
5. *Hypersonic entry + chute guidance adds guidance while on the parachute.*

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This technology task will build a prototype autonomous final approach navigation system capable of on-board processing radiometric tracking data between a MN orbiter and an approach vehicle to achieve 300 m or better atmosphere entry knowledge error (as highlighted in gray in row 2). The resulting technology is enabling for pinpoint landing (i.e., row 3). Ultimately, this navigation technology should be integrated with a Mars approach vehicle's onboard guidance system for complete closed-loop guidance and navigation (GN). Doing so will achieve a 300m or better atmosphere delivery error. However, in the interest of keeping the size of the task modest, this effort addresses only the navigation portion of a complete GN system.

The Mars Network is ideally situated to provide autonomous navigation support using a version of Electra (the MN's next generation software UHF transceiver) that has been programmed to do so during a mission's final approach and terminal phases. [18] A key service of the Mars Network is to provide communications using Electra during mission critical events. Indeed future relay orbiters that will make up the MN, such as the Mars Reconnaisance Orbiter (MRO) or another combined science/relay orbiter being considered for launch in the 2011/2013 timeframe, will have budgeted maneuvering capability to ensure coverage for a Mars mission during its critical event. [19] By design, Electra is also capable of collecting Doppler data concurrent with data transmission while the link is active. Furthermore, Electra has been designed with spare processing and memory capabilities that can be utilized for higher level processing. [20] Electra has a Sparc V7 RISC based processor with a clock speed of 24MHz and about 256 MBits of storage. It is estimated that about 2/3rds of this processing and memory is available for use. Given a baseline scenario, where radiometric data between a MN orbiter and a user vehicle (also carrying a version of Electra) are available, it remains to build a capability to actually utilize this data to enable success of missions with precise terminal phase navigation requirements.

Project Overview and Initial Results

Our plan is to research and develop algorithms and prototype software to be hosted on Electra that can process Electra based radiometric data and determine trajectories during final approach in real-time. Operationally, we expect the navigation to be an autonomous process that can be monitored at Earth in the first few hours after the final TCM, however, the end phase of EDL necessarily occurs in a fully autonomous mode. Initial monitoring will be used as a checkout period by the Earth based ground team to validate the on-board processing. We are developing a prototype capability that can be used as a demonstration of this technology on the Mars Science Laboratory (MSL) which will have a version of Electra on-board. Some key challenges that present themselves include:

(1) Determining navigation algorithms that yield sufficiently precise solutions; yet are robust and efficient.

(2) Characterize the performance of these algorithms with realistic/detailed scenarios.

(3) Characterize Electra sensor acquisition and tracking performance in the presence of weak signals.

(4) Embedding these 'right-sized' algorithms in an emulated Electra and testing in a realistic simulated environment, and then hosting the software on a version of Electra made with commercial parts.

(5) Integrating autonomous real-time approach navigation with its counterpart that is active during the EDL mission phase, integrating the navigation strategy with other sensor data (i.e., accelerometers).

Our plan to meet these challenges is based on an analysis and simulation approach with ever increasing levels of fidelity, and a development approach that yields prototype autonomous approach navigation software that is eminently ready for hosting on a flight version of Electra. Completion of all the objectives and tasks in this proposal will bring the technology from its current level of TRL 3 where studies have shown its feasibility to TRL 5 where an environment relevant demonstration will have been conducted. The final product will be a *unique* application of MN services that can provide an autonomous final approach navigation capability at Mars. The Mars Approach Navigation using In-Situ Orbiters task consists of a two-year effort culminating in a prototype approach navigation system that can be hosted on Electra and will be proposed for demonstration on MSL.

First Year Accomplishments

In Year 1, the objective was on conceptual development and simulation. We achieved a number of specific objectives including:

Development of a representative detailed Mars approach scenario using a nominal MSL approach trajectory and Mars Network tracking from the, now defunct, Mars Telecom Orbiter. On the cancellation of MTO we began to transition our scenario to using MRO. We are currently processing the impacts of this switch. Foremost of which will be a decrease in the maximum signal acquisition distance. For MTO acquisition was anticipated at 10 – 12 hrs prior to entry, for MRO this will most likely reduce to just a few hours. It should be noted that these acquisition distances are based on specified and margined link conditions, it is anticipated that Electra's actual receive sensitivity (as currently demonstrated in the lab) will extend these acquisition times by 2 to 3 times. The scenario work provides a basis for simulating expected performance of the navigation algorithms and providing a truth model for testing the performance of the algorithms on the target hardware. Some initial results of this simulation capability are shown in Figure 7. The two plots depict the 1-sigma semi-major axis of the current state position uncertainty for a simulated MSL approach trajectory in the final day prior to entry (left plot), and from separation to landing (right plot). The plots depict 6 tracking scenarios:

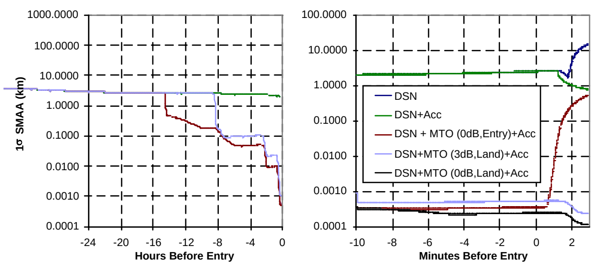

Figure 7: Illustration of trajectory knowledge produced by a MN orbiter tracking Mars approach vehicle.

DSN with a blue line: 2-Way Doppler, Range, and Delta-DOR from DSN stations located at Goldstone, Madrid, and Canberra. This level of DSN support provides 24 hour coverage. The data cut off is at 6 hours prior to entry which is nominal for MSL. For this case, after data cutoff the trajectory error simply maps forward in time till landing. The entry trajectory is simulated as a ballistic entry (note that MSL is baselining a hypersonic guided flight phase – this will be discussed shortly). Because the entry is ballistic the landing errors are more representative of a MER-class EDL system. Indeed, the stochastic drag model used in the simulations has been selected such that the 1-sigma landed error of about 11 km matches the predicted MER landed error. The other significant result is the error at the atmospheric interface (i.e., at 125 km altitude) which is ~ 2 km differs slightly from the anticipated MSL delivery error of ~ 1.5 km. The difference between the result in Figure 7 and the MSL estimate occurs because our simulation uses only 30 days of tracking data, whereas MSL simulations routinely use 60 day arcs. We are in the process of updating the simulation to include the longer tracking arc.

DSN + Acc with a green line: This is the same scenario as before, however now there is simulated accelerometer data being processed by the filter to obtain trajectory knowledge updates. As mentioned previously, MSL will fly hypersonic guided flight by using modulated lift via bank angle control in order to fly a nominal drag profile as measured by on-board accelerometers. The fact that the measurements are used to maintain a nominal flight profile is akin to using the measurements in a filter to maintain trajectory knowledge. This fact is reflected in the atmospheric flight trajectory knowledge improvement seen in the results where the landed 1-sigma uncertainty improves from Case (a) to approximately 1 km. It should be noted that for these initial results the accelerometer model includes only noise errors, and not any bias errors. It is anticipated that inclusion of bias errors will lead to a result where the error at the top of atmosphere remains constant rather than decreasing. The basis for this statement derives from Monte Carlo simulations of guided MSL (conducted by the MSL project team) entry where the trajectory error remains relatively constant throughout the guided entry portion of EDL.

DSN + MTO (0 dB, Entry) + Acc with a red line: This case builds on Case (b) except now there is 2-Way Doppler data being collected between MSL and MTO. The data starts with at zero margin acquisition sensitivity of Electra (at -140 dBm) which correlates into acquisition at about 15 hours prior to entry. There are 4 passes of data each of about 45 minutes in length with the last pass ending with a data cutoff at atmosphere entry. The flight through the atmosphere includes accelerometer data. The results clearly indicate the value of the Mars Network based Doppler tracking data, indeed, the uncertainty at the top of the atmosphere has decreased to less than 1 m 1-sigma. This result vividly displays the utility of using MN based tracking data at improving Mars-relative trajectory knowledge. The important point about the results of this case is that the accelerometer is unable to maintain this level of trajectory knowledge during the hypersonic guided flight phase of the mission. The trajectory error grows to nearly 1 km 1-sigma by landing. To maintain trajectory knowledge at the 10s of meter level requires additional MTO based tracking during the EDL phase of the flight. This is demonstrated in the following Cases (d) and (e).

DSN+MTO (3 dB, Landing) + Acc with the lavender line: This case differs from Case (c) in two ways. First, the Electra acquisition sensitivity includes a 3 dB margin leading to acquisition at about 10 hours prior to entry. Second, MTO tracking is through the entire EDL phase to landing. In this case, the entry knowledge of less than 1 m is maintained throughout atmospheric flight. It should be emphasized that a key error source not included in this result is the map tie error relating knowledge of the inertial frame to the Mars body fixed frame. Current estimates place this error at around 150 m 1-sigma. Hence, the landed error in this example related to the Mars surface map is at this level.

DSN+MTO (0 dB, Landing) + Acc with the black line: This is the same as Case (d) however it uses the zero margin acquisition distance. The results are qualitatively and, essentially, quantitatively the same as the results shown for Case (d).

Development of a precise model for Electra's 1-Way and 2-Way integrated Doppler radiometric data, and navigation algorithms sufficient to determine approach trajectories that satisfy atmosphere delivery requirements for pinpoint landing. We are currently implementing a factorized filtering algorithm, doing so ensures the navigation process remains numerically stable through out the final approach navigation phase.

Characterized MSL and MTO/MRO scenario link dynamics and strength using realistic assumptions about the relative dynamics between the spacecraft, antenna gain patterns, and other link budget factors affecting the signal strength. The next step is to simulate Electra acquisition and tracking performance in the presence of these signals using a Matlab simulation of Electra's analog/digital signal processing.

Development of an Electra processor software/hardware emulation capability that allows us to develop and test software performance in a realistic environment that emulates the real time performance Electra processor and memory. Hosted the filtering time update equations in the emulator, currently implementing the factorized measurement update equations.

The preceding accomplishments have been encouraging, and give us confidence that we will be able to meet our 2nd year objectives outlined next.

Second Year Objectives

The Year 2 objective will be to host and test the developed algorithms in a realistic hardware environment. Specific tasks include:

(1) Perform trades to optimize navigation software for hosting on an Electra processor, including selection of necessary propagation algorithms.

(2) In tandem with the above trades, complete hosting the, software on the emulated Electra processor, and on the hardware testbed.

(3) Test prototype navigation software in emulation/testbed via simulation.

(4) Test Electra acquisition and tracking performance with simulated signals.

(5) Write a final report documenting our results.

(6) Develop plans, in conjunction with the Mars Technology Program, with options for further developing this technology with the eventual aim of a flight demo on MSL.

Summary

Existing missions such as MSL are being designed with landing errors that are consistent with existing technologies. For instance, MSL is designing for a 10 km (3-sigma) error on landing. This is characteristic of what has been termed a "Generation 2" lander. However, to achieve "Generation 3" pinpoint landing accuracies of 10's of meters to 1 km requires advances in navigation and guidance technology. The technology proposed here is relevant to any Generation 3 type landings, or any Mars mission requiring precision approach trajectory information. Demonstration of precision approach using the Mars Network will pave the way to achieving sub-1 km pinpoint landing accuracies. Without improving final approach trajectory knowledge (using whatever means) it simply will not be possible to achieve this objective. That is, a guidance system can not correct for trajectory errors that it has no "knowledge" of. The Mars Network brings a capable and available sensor (namely Electra) to help solve this problem; this technology effort will use this critical resource in a novel and efficient way. Successful completion of these objectives will be enabling for future NASA Mars science investigations that have precision landing. NASA's Roadmap for Solar System Exploration [17] states that Mars exploration is "discovery driven," meaning future missions rely on the findings of earlier missions. This concept coupled with scientist's call for a sample return mission lead to the following conclusion (excerpt from the NASA SSE Roadmap):

"These sample return missions must have a 'Go To' capability in which safe precision landing, coupled with mid-to long-range mobility, can acquire key samples retrieved from highly localized surface targets such as an outcrop of sedimentary rock or a drill hole."

Clearly, achieving "Go To" driven science goals requires getting there accurately; autonomous approach navigation is a vital step towards meeting these ends.

CONCLUSIONS

This work is part of a broader effort to improve space communications through a combination of networking of space assets and application of techniques to improve the effectiveness of communication links. Future investments in this area could include Quality of Service protocols, space-based middleware services, demand-access techniques, and techniques for automating network operations.

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